Cold Regions Science and Technology 124 (2016) 110–117

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Bidirectional-reflectance measurements for various snow crystal morphologies

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ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form 2 December 2015
Accepted 31 December 2015
Available online 21 January 2016

Keywords:
Surface hoar
Rounded grains
Snow reflectance
BRDF
Albedo
BRF

ABSTRACT

An understanding of snow optical properties is vital to accurately quantifying the effect of snow cover on the Earth's radiative energy balance. Central to these models is the need for accurate bidirectional reflectance data for various snow surface types. However, few studies in this area exist and none focus specifically on surface hoar—a well-known surface crystal type often responsible for avalanches.

In this study, it is postulated that the bidirectional reflectance distribution of the snow's surface before and after surface hoar growth will be predictably and quantifiably different when viewed in the visible wavelengths. To test this hypothesis, a methodology for reliably growing surface hoar in a lab setting was developed. Temporal changes in crystal habit were documented using computed tomography and visible microscopic imaging. A spectrometer was used to measure bidirectional-reflectance factors (BRF) both before and after surface hoar growth. Analysis of the results revealed three primary conclusions: 1) Surface hoar growth is accompanied by a departure from Lambertian scattering. The effect is more apparent the larger the surface hoar grains. 2) The incident lighting and viewing geometries at which maximum and minimum BRF values occur are difficult to discern. 3) In the transition from rounded grains to surface hoar, spectral albedo (as calculated by averaging the BRF over a hemispheric solid angle at 510 nm) decreases slightly.

1. Introduction

Advances in satellite remote sensing capabilities have introduced the need for accurate multi-angle reflectance studies at a high temporal and spatial resolution for the plethora of snow crystal morphologies in existence (Bruegge et al., 2000). To address this need, this study focuses on the bidirectional reflectance of two distinct snow surface types: rounded grains and surface hoar. Multi-angle studies focused on capturing crystal habit effects often report results in terms of a bidirectional reflection distribution function (BRDF) or a bidirectional-reflectance factor (BRF). As the name implies, a BRDF "describes the scattering of a parallel beam of incident light from one direction in the hemisphere into another direction in the hemisphere" (Bruegge et al., 2000; Nicodemus et al., 1977). BRDF is the ratio of radiance L (W m^{-2} sr^{-1}) exiting the surface in a single direction to the incident irradiance E (W m^{-2}) from a single direction,

$$BRDF = \frac{dL_r(\theta_i, \phi_i, \theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)}\left[sr^{-1}\right]. \quad (1)$$

This ratio is a function of reflectance azimuth (θ_r) and zenith (ϕ_r) angles, as well as incident zenith (θ_i) and azimuth (ϕ_i) angles and, finally, wavelength (λ) (Fig. 1). Note that, in this study, the azimuth is defined relative to the incident light such that $\phi_i = 180°$.

Hemispherically integrating the BRDF across all azimuth and zenith angles yields the albedo (α),

$$\alpha(\theta_i) = \int_0^{2\pi}\int_0^{\frac{2}{\pi}} f_r(\theta_i, \phi_i, \theta_r, \phi_r)\cos\ \theta_r \sin\theta_r d\theta_r d\phi_r, \quad (2)$$

the ratio of all exiting light to all incident light across the entire hemisphere and across all wavelengths. Spectral albedo is albedo at a particular wavelength.

Because it is a ratio of infinitesimal properties, the BRDF cannot be measured directly (Schaepman-Strub et al., 2006). In studies where reflection is measured directly, results are reported in terms of a BRF value, a unitless ratio of power $\Phi_{r,snow}$ reflected from the snow surface to the power $\Phi_{r,ideal}$ reflected from a commercially available Lambertian reference standard such as Spectralon,

$$BRF = \frac{\Phi_{r,snow}(\theta_i, \phi_i, \theta_r, \phi_r)}{\Phi_{r,ideal}(\theta_i, \phi_i)}. \quad (3)$$

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http://dx.doi.org/10.1016/j.coldregions.2015.12.011
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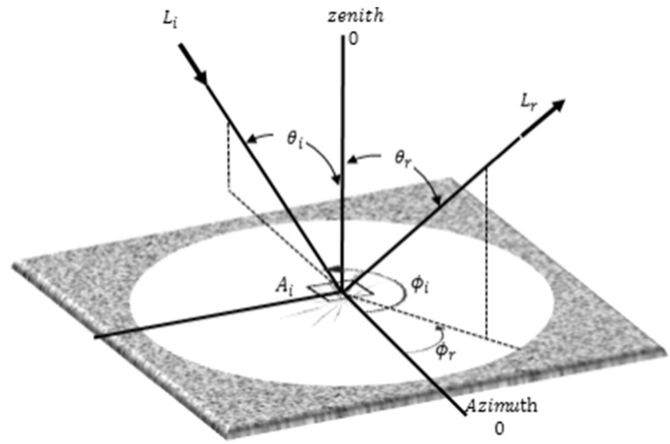

Fig. 1. Reflectance azimuth (θ_r) and zenith (ϕ_r) angle as well as incident zenith (θ_i) and azimuth (ϕ_i) angle. In this study, 0 azimuth is defined relative to the incident light such that $\phi\_i = 180°$.

Like BRDF, averaging the BRF over a hemispheric solid angle produces the albedo, which expresses a ratio of the reflected and incident irradiances.

After field observations made by eye suggested a difference in the reflective properties of rounded grains and surface hoar, it was hypothesized that microstructural changes due to the deposition of faceted surface hoar crystals at the snow's surface will alter the visible bidirectional reflectance as compared to rounded grains. Specifically, it was postulated that the BRF of the snow's surface before and after surface hoar growth would be predictably and quantifiably different.

To test this hypothesis, a methodology for growing surface hoar in a lab setting was developed. Both microscopic and computed tomography (CT) images were used to document snow grain habit before and after surface hoar growth. Once various surface hoar morphologies were predictably and reliably grown in the lab, protocols for optical testing were developed and carried out on two distinct crystal morphologies: rounded grains and plate-like surface hoar—i.e. surface hoar dominate by crystallographic a-axis growth (Nakaya, 1954). The resulting CT and microscopic images as well as BRF values for both grain types are presented.

2. Background

In practice, field studies using the sun as the illumination source have both a direct component and a diffuse component that arises from atmospheric scattering. These studies often report a hemispherical–directional reflectance factor (HDRF) to indicate that the result includes incident light scattered by the atmosphere. HDRF values, which depend on daily atmospheric conditions, are of limited use in comparison to BRDF.

Leroux et al. (1998) performed ground HDRF (later converted to BRDF) measurements in the near and short-wave infrared, out to 1650 nm, for clustered rounded grains, faceted and fine particles, and faceted crystal/surface hoar. Though not specified in the discussion of their measured results, observation of their reflectance data suggests that, at 1650 nm, the BRDF of rounded grains varies significantly less than the BRDF of surface hoar.

Similarly, Aoki et al. (2000) measured HDRF data in the 350 to 2500 nm range for new snow, granular snow, and faceted crystals but does not indicate whether the faceted crystals were surface hoar. The study concludes that BRDF showed significant anisotropy in the NIR, but was generally insensitive to grain shape in the visible range.

Painter and Dozier (2004) measured HDRF values for fine-grained, decomposed dendritic forms and medium sized clustered grains after a melt–freeze cycle. They noticed the fine-grain faceted snow "exhibited a local backscattering peak at the view zenith near the solar zenith angle, whereas (the HDRF) for medium grain, clustered snow did not have a local backscattering peak." Further, an increase in grain radius from 80 μm to 280 μm was accompanied by a decrease in the HDRF for all wavelengths.

Li and Zhou (2004), performed HDRF measurements (and later translated the results into BRF values) in the 350–1050 nm range on rounded, sintered, composite coarse grains overlain by broken fine particles and solid, faceted, coarse particles overlain by fine grains. They looked at large solar zenith angles (65° and 85°). The results showed that these snow types had a strong forward-scattering peak under large solar incidence angles.

Similarly, Bourgeois et al. (2006) performed HDRF (350–1050 nm) studies in Greenland on wind-broken small grained snow and a surface covered with rime causing a higher surface roughness. They found a wide range of HDRF values (from 0.6 to 13) depending on the solar zenith angle. It varied from nearly isotropic at nadir illumination angles to highly forward-scattering at solar zenith angle of 85°. Additionally, surfaces covered with rime exhibited less forward-scattering than smooth surfaces.

Dumont et al. (2010), using a methodology similar to the one used here, looked at the directional dependence of 4 different grains (dendritic fragments, clustered rounded grains, melt freeze crusted grains, new wet snow) over a wide range of lighting and viewing geometries. They concluded that both grain size and shape have an effect on the reflectance distribution (primarily in the NIR and longer wavelengths) but that it is difficult to predict. Further, they were able to distinguish a recognizable reflectance pattern for elongated or faceted shapes. Specifically, they noted darkening at viewer grazing angles in situations of near

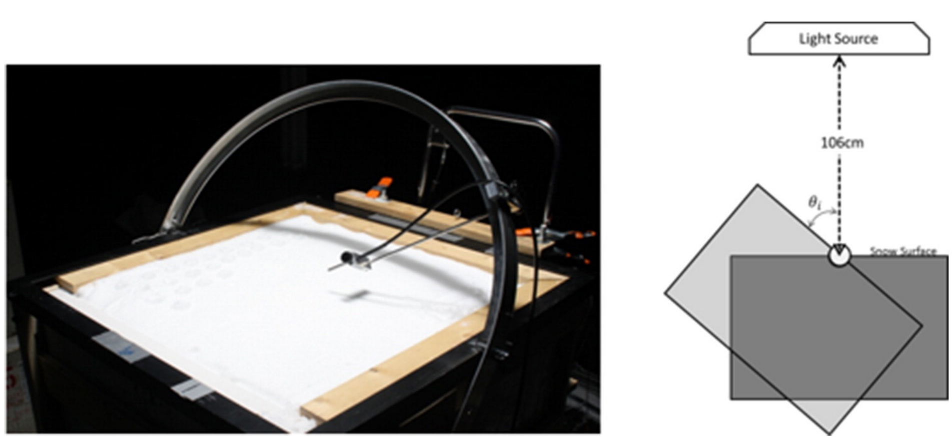

Fig. 2. Left: Goniometer and spectrometer configuration. Right: Sun angle θ_i was varied by tilting the snow surface with respect to the fixed light source.